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14. ABSTRACT

This report describes the main research achievements during the time period cited above on the research project in the area of wireless communications. The main achievements include new design criteria for space-time codes (STC) to achieve full diversity with partial interference cancellation (PIC) group decoding and conditional PIC group decoding and new STC designs of high rates satisfying the proposed new design criteria for MIMO and cooperative communication systems, and a distributed cooperative coding scheme with low probability of interception.

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full diversity with partial interference cancellation (PIC) receivers, distributed space-time codes, MIMO-OFDM, relay networks, asynchronous diversity, low probability of interception

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A. **Objective**: The goal of this research is to design space-time codes/modulations for multi-input multi-output (MIMO) and cooperative communication systems that achieve full spatial diversity when low complexity receivers, such as zero-forcing (ZF), minimum mean square error (MMSE), or decision feedback equalizer (DFE) receivers, are used.

B. **Main Research Accomplishments (during the reporting period)**: We have made several major research accomplishments as follows.

(i) *New Criterion and Constructions of Space-Time Block Codes Achieving Full Diversity with Partial Interference Cancellation Algorithm*: We obtained a partial interference cancellation (PIC) group decoding for linear dispersive space-time block codes (STBC) and a design criterion for the codes to achieve full diversity when the PIC group decoding is used at the receiver. A PIC group decoding decodes the symbols embedded in an STBC by dividing them into several groups and decoding each group separately after a linear PIC operation is implemented. It can be viewed as an intermediate decoding between the maximum likelihood (ML) receiver that decodes all the embedded symbols together, i.e., all the embedded symbols are in a single group, and the zero-forcing (ZF) receiver that decodes all the embedded symbols separately and independently, i.e., each group has and only has one embedded symbol, after the ZF operation is implemented. The PIC group decoding provides a framework to adjust the complexity-performance tradeoff by choosing the sizes of the information symbol groups. Our proposed design criterion (group independence) for the PIC group decoding to achieve full diversity is an intermediate condition between the loosest ML full rank criterion of codewords and the strongest ZF linear independence condition of the column vectors in the equivalent channel matrix. We also proposed asymptotic optimal (AO) group decoding algorithm which is an intermediate decoding between the MMSE decoding algorithm and the ML decoding algorithm. The design criterion for the PIC group decoding can be applied to the AO group decoding algorithm too. It is well-known that the symbol rate for a full rank linear STBC can be full, i.e., n_t for n_t transmit antennas. It has been recently shown that its rate is upper bounded by 1 if a code achieves full diversity with a linear receiver. The intermediate criterion we obtained provides the possibility for codes of rates between n_t and 1 that achieve full diversity with a PIC group decoding. This therefore provides a complexity-performance-rate tradeoff. We obtained a systematic space-time block code designs with a particular grouping scheme that satisfy the above proposed design criterion,

i.e., achieve full diversity with the PIC group decoding.

We obtained a systematic design of full-diversity STBC with low-complexity PIC group decoding. The proposed code design is featured as a group-orthogonal STBC by replacing every element of an Alamouti code matrix with an elementary matrix composed of multiple diagonal layers of coded symbols. With the PIC group decoding and a particular grouping scheme, the proposed STBC can achieve full diversity, a rate of $(2M)/(M+2)$ and a low-complexity decoding for M transmit antennas. Our simulation results show that the proposed codes can achieve the full diversity with PIC group decoding while requiring half decoding complexity of the existing codes.

We obtained a new systematic design of space-time block codes (STBC) which can achieve high rate and full diversity when the partial interference cancellation (PIC) group decoding is used at receivers. The proposed codes can be applied to any number of transmit antennas and admit a low decoding complexity while achieving full diversity. For M transmit antennas, in each codeword real and imaginary parts of PM complex information symbols are parsed into P diagonal layers and then encoded, respectively. With PIC group decoding, it is shown that the decoding complexity can be reduced to a joint decoding of $M/2$ real symbols. In particular, for 4 transmit antennas, the code has real symbol pairwise (i.e., single complex symbol) decoding that achieves full diversity and the code rate is 4/3. Our simulation results demonstrated that the full diversity is offered by the newly proposed STBC with the PIC group decoding.

We obtained a new family of space-time block codes (STBC) that achieve full diversity when linear receivers, such as zero-forcing (ZF) or minimum mean square error (MMSE) receivers, are used. Our newly obtained STBC family is a combination/overlay between orthogonal STBC and Toeplitz codes, which could be viewed as a generalization of overlapped Alamouti codes (OAC) and Toeplitz codes recently proposed in the literature. It is shown that the newly proposed STBC may outperform the existing codes when linear receivers are used.

(ii) *New Space-Time Block Codes Designs Based Conditional Partial Interference Cancellation (PIC) Group Decoding*:

Space-time code designs based on a partial interference cancellation (PIC) group decoding has been proposed previously from this project. The PIC group decoding complexity depends on the group size and is between the lowest linear receiver complexity and the highest ML decoding complexity. The symbol rate for a space-time code achieving full diversity with the PIC group decoding is also between those for the

linear receivers and the ML decoding. In this new work, we proposed a new decoding that is between the PIC group decoding and the ML decoding. With the proposed new decoding, we obtained a new design criterion for space-time codes to achieve full diversity, which is also between the one with the PIC group decoding and the one with the ML decoding. We then presented some new code designs that satisfy the new criterion and in the meantime have higher symbol rates than that for the PIC group decoding.

(iii) *A Distributed Differentially Encoded OFDM Scheme for Asynchronous Cooperative Systems with Low Probability of Interception*: Recently, a physical-layer security design to guarantee low probability of interception (LPI) for MIMO systems without relying on upper-layer data encryption has been proposed in the literature. The proposed scheme utilizes antenna array redundancy to deliberately randomize the transmitted signals to prevent eavesdropping. In our work we designed a physical-layer transmission scheme to achieve LPI in cooperative systems. There are two major differences in cooperative systems: 1) each relay node may have only one antenna that can not provide antenna array redundancy for signal randomization; 2) there may exist timing errors due to the asynchronous nature of cooperative systems. Considering the two differences, we proposed a distributed differentially encoded OFDM transmission scheme with deliberate signal randomization to prevent eavesdropping and exploit the available spatial and frequency diversities in asynchronous cooperative systems. We use diagonal unitary codes to perform the differential encoding in the frequency domain over subcarriers within each OFDM block, or we use general (not necessarily diagonal) unitary codes to perform the differential encoding in the frequency domain across several OFDM blocks. By some deliberate signal randomization, the eavesdropper can not detect the transmitted symbols, while the authorized receiver can perform differential decoding successfully without the knowledge of the channels or the timing errors.

(iv) *New Space-Time Codings for Asynchronous Cooperative Systems*: We obtained a new and simple orthogonal space time transmission scheme for asynchronous cooperative systems with frequency selective fadingm channels. In the proposed scheme, OFDM is implemented at the source node, some very simple operations, namely time reversion and complex conjugation, are implemented at the relay nodes, and a two-step of cyclic prefix (CP) removal is performed at the destination. The CP at the source node is used for combating the frequency selective fading channels and the timing errors. In this scheme, the received signals at the destination node have the orthogonal

code structure on each subcarrier and thus it has the fast symbol-wise ML decoding and can achieve full spatial diversity when SNR is large without the requirement of symbol level synchronization. It should be emphasized that since no Add/Remove CP or IFFT/FFT operation is needed at the relay nodes, the relay nodes do not have to know any information about the channels and the timing errors, and the complexity of the relay nodes is very low.

We obtained a new analog network coding (ANC) scheme for a general time asynchronous two-way relay network, where two terminal nodes exchange information through multiple relay nodes. In the proposed scheme, each relay node linearly transforms the received mixed asynchronous signals in the first time-slot by a Toeplitz matrix, and then broadcasts them back to the terminals in the second time-slot. A sufficient condition for the proposed ANC to achieve full cooperative diversity using only linear receivers at the terminal nodes, such as zero-forcing (ZF), or minimum mean square error (MMSE) receivers, with any delay profiles of the timing errors was derived. Furthermore, a systematic construction which satisfies the sufficient condition was also proposed. The symbol rate of the proposed ANC scheme can approach 1 when the coding block length is sufficiently large compared to number of relay nodes R and the timing errors.

We obtained a space-time coding scheme for asynchronous two-way relay networks where two sources exchange information through the relay nodes. In our proposed scheme, we consider a wireless scenario with frequency selective fading channels. Orthogonal frequency-division multiplexing (OFDM) is implemented at the two sources and then the OFDM blocks are transmitted to the relay nodes in the first time slot. In the second time slot, at the relay nodes, the ANC that has a few simple operations are implemented on the received mixed signals and then the processed signals are broadcasted to the two sources to finish the information exchange. In this scheme, at each source, when recovering the designed information transmitted from another source, the received signals have the orthogonal space time block code (OSTBC) structure or the quasi-orthogonal space time block code (QOSTBC) structure on each subcarrier. By a proper power allocation, the two sources can achieve full spatial diversity and fast ML decoding without the requirement of symbol level synchronization. By the repetition across the subcarriers, multi-path diversity available in frequency selective fading channels can be also exploited. Moreover, the proposed ANC scheme is also valid for multi-way relay networks where multiple sources exchange information.

In cooperative communications, due to the distributed nature, multiple different carrier frequency offsets (CFOs) may occur and make the channel time-varying. It is hard for the receiver to compensate multiple CFOs from multiple relay nodes simultaneously. Thus, the conventional space-time codes to collect cooperative diversity for co-located multi-input multi-output (MIMO) systems may not be applied directly. We have considered the cooperative transmission with multiple CFOs when the channels from relay nodes to destination node are flat (frequency-non-selective) fading. We have approximated a flat fading channel with CFO as a block time-invariant intersymbol-interference (ISI) channel in the frequency domain. We have then proposed two distributed space-frequency codes (SFC) for such ISI channels in the frequency domain to achieve the cooperative full spatial diversity, where the space-frequency coding concept is different from the one in the literature and also has a different role. One is called *frequency-reversal SFC* and the other is called *frequency-domain linear convolutive SFC*. Furthermore, we show that, with only linear receivers, such as zero-forcing (ZF) and minimum mean square error (MMSE) receivers, our codes achieve the full cooperative diversity.

We obtained a new time domain interference cancellation for Alamouti coded cooperative OFDM systems with insufficient CP. OFDM transmission has been proposed in the literature for relay nodes to combat the time delays from the relay nodes, where the paths from relay nodes to destination node are treated as multipaths and space-time (or frequency) coding is used to achieve the spatial (or multipath) diversity. With this approach, when the cyclic prefix (CP) length is less than the time delay length, inter-block interference occurs. In this work, we considered Alamouti coded OFDM systems in cooperative communications where the CP length may be less than the time delay length. By taking the advantage of the Alamouti code structure, we proposed a new time domain interference cancellation algorithm. Simulation results show that the performance is significantly improved with our newly proposed time domain interference cancellation algorithm.

(v) *Signal Space Diversity Techniques with Fast Decoding Based on MDS Codes*: In wireless communication systems, signal space diversity techniques are usually adopted to combat channel fading by exploiting time diversity, frequency diversity, spatial diversity or a combination of them. Most existing schemes to achieve signal space diversity are based on linear constellation spreading. In this work, we proposed a novel nonlinear signal space diversity technique based on maximum distance separable (MDS) codes. The new technique provides a design flexibility for almost any number of diversity chan-

nels and desired diversity orders. We also proposed a simple and suboptimal diversity channel selection (DCS) decoding for our new scheme. DCS decoding can greatly reduce the decoding complexity at a cost of marginal performance loss relative to the optimal detection while keeping the diversity order. Our simulation results showed that with the same throughput but a lower decoding and implementation complexity, our scheme can have superior performance than the optimal linear spreading schemes over either independent fading or additive white Gaussian noise (AWGN) channels.

(vi) *A Robust Chinese Remainder Theorem with its Applications in Frequency Estimation from Undersampled Waveforms*: Chinese remainder theorem (CRT) is to reconstruct a large integer from its remainders modulo several moduli. In this work, we have obtained a robust reconstruction algorithm called robust CRT when the remainders have errors. We show that, using the proposed robust CRT, the reconstruction error is upper bounded by the maximal remainder error range named remainder error bound, if the remainder error bound is less than one quarter of the greatest common divisor (gcd) of all the moduli. The robust CRT can be applied to estimate frequencies when the signal waveforms are undersampled multiple times. It shows that with the robust CRT, the sampling frequencies can be significantly reduced.

Based on an adaptive IIR notch filter and our proposed robust CRT, we have obtained a frequency estimation algorithm from multiple undersampled signals. Our proposed algorithm can significantly reduce the sampling rates and provide more accurate estimates than the method based on adaptive IIR notch filter and sampling rates above the Nyquist rates does.

We obtained a fast robust phase unwrapping algorithm. We proposed a robust phase unwrapping based on Chinese remainder theorem (CRT) previously and it has applications in synthetic aperture radar (SAR) imaging for moving targets. This algorithm requires a two dimensional searching. We obtained a new and fast algorithm that only does one dimensional searching and therefore reduces the complexity significantly.

We also proposed a robust algorithm for Doppler ambiguity resolution based on a recently developed robust phase unwrapping algorithm and the Ferrari-Bérenguer-Alengrin (FBA) method using multiple pulse repetition frequencies (PRF). In the FBA method, the PRFs are grouped into pairs and each paired PRF values are symmetric about 1, then the Doppler frequency estimation is divided into two steps (folded frequency, i.e., the fractional part, and ambiguity order, i.e., the integer part): the folded frequency is estimated by circularly averaging the folded frequency estimates

for each pair PRF and the ambiguity order is obtained by searching the finite integers based on a quasi maximum-likelihood criterion using the estimated folded frequency. By observing that the folded frequency estimates for each pair PRF may have errors due to the finite FFT implementations, noise, and interference, the circular mean of the erroneous folded frequency estimates may be erroneous too, which may lead to an erroneous ambiguity order estimate, i.e., a large error. In this work, we replace the integer ambiguity order searching by a recently developed robust phase unwrapping algorithm that is robust to the frequency estimates from the FFT implementations. Our simulation results show that the newly proposed algorithm significantly outperforms the FBA method.

Synthetic aperture radar (SAR) location and imaging of moving targets in clutter have attracted much attention in recent years. Locations of moving targets in SAR images are determined not only by their geometric locations but also by their velocities that cause their SAR images de-focused, smeared, and mis-located. With a linear antenna array, velocity synthetic aperture radar (VSAR) can detect, focus, and locate slowly moving targets well. However, it may mis-locate fast moving targets in the azimuth (cross-range) direction, and sometimes even in the ground range direction if the targets are elevated above the ground. Although multiple frequency antenna array SAR (MFAASAR for short) can solve the azimuth mis-location, it still leaves the ground range migration of elevated targets unsolved. In this work, we proposed an antenna array approach with cross-track interferometry, in which multiple wavelength signals are transmitted. We then proposed a robust Chinese remainder theorem (CRT) based phase unwrapping algorithm. The proposed robust CRT based phase upwrapping algorithm is robust to signal noise, which is different from the the conventional CRT based phase unwrapping algorithm that is highly sensitive to signal noise and non-robust. It was shown that our proposed multiple-frequency interferometric velocity SAR (MFIn-VSAR) by applying our proposed robust phase unwrapping algorithm can locate both slowly and fast moving elevated targets correctly. An integrated MFIn-VSAR algorithm for moving target imaging was also presented.

C. Significance:

The obtained new criteria on space-time code designs achieving full diversity with partial interference cancellation (PIC) algorithms will result in important practical space-time codes that can achieve the ultimate trade-off of diversity-multiplexing-complexity. These new codes will impact the near future high speed wireless communication stan-

dards and products. To design these codes, some advanced mathematics, such as algebraic number theory, may be needed and progressed. The robust CRT we have developed will have important applications in radar imaging of targets.

D. **Publications, Abstracts, Technical Reports, and Patent Disclosures or Applications** (during the reporting period):

Refereed Journal Publications Supported by the Grant (Submitted)

35. W. Zhang, T. Xu, and X.-G. Xia, Two Designs of Space-Time Block Codes Achieving Full Diversity with Partial Interference Cancellation Group Decoding, submitted to *IEEE Trans. on Information Theory* (revised).

Refereed Journal Publications Supported by the Grant (Published and Accepted)

34. T. Xu and X.-G. Xia, On Space-Time Code Design with A Conditional PIC Group Decoding, *IEEE Trans. on Information Theory*, accepted for publication.

33. H. Wicaksana, S. H. Ting, Y. L. Guan, and X.-G. Xia, Decode-and-forward two-path half-duplex relaying: diversity-multiplexing tradeoff analysis, *IEEE Trans. on Communications*, accepted for publication.

32. L. Shi, W. Zhang, and X.-G. Xia, High-rate and full-diversity space-time block codes with low complexity partial interference cancellation group decoding, *IEEE Trans. on Communications*, accepted for publication.

31. X.-Q. Gao, W. Wang, X.-G. Xia, X. You, and E. K. S. Au, Cyclic Prefixed OQAM-OFDM and Its Application to Single-Carrier FDMA, *IEEE Trans. on Communications*, accepted for publication.

30. H.-M. Wang, X.-G. Xia, and Q.-Y. Yin, Full Diversity Space-Frequency Codes for Frequency Asynchronous Cooperative Relay Networks with Linear Receivers, *IEEE Trans. on Communications*, accepted for publication.

29. X. W. Li and X.-G. Xia, Location and Imaging of Elevated Moving Target Using Multi-Frequency Velocity SAR with Cross-Track Interferometry, *IEEE Trans. on Aerospace and Electronic Systems*, April 2011.

28. H.-M. Wang, X.-G. Xia, and Q.-Y. Yin, A Linear Analog Network Coding for Asynchronous Two-Way Relay Networks, *IEEE Trans. on Wireless Communications*, vol. 9, pp. 3630-3637, Dec. 2010.

27. H.-M. Wang, Q.-Y. Yin, and X.-G. Xia, Fast Kalman Equalization for Time-Frequency Asynchronous Cooperative Relay Networks with Distributed Space-Time Codes, *IEEE Trans. on Vehicular Technology*, Nov. 2010.

26. W.-J. Wang and X.-G. Xia, A Closed-Form Robust Chinese Remainder Theorem and Its Performance Analysis, *IEEE Trans. on Signal Processing*, Nov. 2010.

25. Y. Shang, D. Wang, and X.-G. Xia, Signal Space Diversity Techniques With Fast Decoding Based on MDS Codes, *IEEE Trans. on Communications*, Sept. 2010.

24. Z. Li, X.-G. Xia, and M. H. Lee, A simple orthogonal space-time coding scheme for asynchronous cooperative systems for frequency slective fading channels, *IEEE Trans. on Communications*, August 2010.

23. Z.-F. Li and X.-G. Xia, Time domain interference cancellation for Alamouti coded cooperative OFDM systems with insufficient CP, *IEEE Trans. on Vehicular Technology*, July 2010.

22. X. Guo and X.-G. Xia, Correction to "On Full Diversity Space-Time Block Codes with Partial Interference Cancellation Group Decoding" *IEEE Trans. on Information Theory*, July 2010.

21. X. Li and X.-G. Xia, A Robust Doppler Ambiguity Resolution Using Multiple Paired Pulse Repetition Frequencies, *IET Radar, Sonar & Navigation*, June 2010.

20. F. Tian, X.-G. Xia, K. Ma, and P. C. Ching, On the full diversity property of a space-frequency code family with multiple frequency offsets in cooperative communication systems, *Journal of Communications*, vol. 5, no. 4, pp. 317-331, 2010.

19. G. Wang, W. Su, and X.-G. Xia, Orthogonal-Like Space-Time Coded CPM Systems with Fast Decoding for Three and Four Transmit Antennas, *IEEE Trans. on Information Theory*, March 2010.

18. H. Wang, X.-G. Xia, Q. Y. Yin, and B. Li, A Family of Space-Time Block Codes Achieving Full Diversity with Linear Receivers, *IEEE Trans. on Communications*, Dec. 2009.

17. Z. Li, X.-G. Xia, and B. Li, Achieving Full Diversity and Fast ML Decoding via Simple Analog Network Coding for Asynchronous Two-Way Relay Networks, *IEEE Trans. on Communications*, Dec. 2009.

16. X. Li, H. Liang, and X.-G. Xia, A Robust Chinese Remainder Theorem with

its Applications in Frequency Estimation from Undersampled Waveforms, *IEEE Trans. on Signal Processing*, Nov. 2009.

15. H. Liang, X. Li, and X.-G. Xia, Adaptive Frequency Estimation with Low Sampling Rates Based on Robust Chinese Remainder Theorem and IIR Notch Filter, *Advances in Adaptive Data Analysis*, vol. 1, no. 4, pp. 587-600, Oct. 2009.

14. X. Guo and X.-G. Xia, On full diversity space-time block codes with partial interference cancellation group decoding, *IEEE Transactions on Information Theory*, Oct. 2009.

13. F. Tian, X.-G. Xia, P. C. Ching, and W.-K. Ma, Signal detection in a space-frequency coded cooperative communication system with multiple carrier frequency offsets by exploiting specific properties of the code structure, *IEEE Transactions Vehicular Technology*, Sept. 2009.

12. Z. Li and X.-G. Xia, A distributed differentially encoded OFDM scheme for asynchronous cooperative systems with low probability of interception, *IEEE Transactions Wireless Communications*, July 2009.

11. Y. Shang and X.-G. Xia, On fast recursive algorithms for V-BLAST with optimal ordered SIC detection, *IEEE Transactions on Wireless Communications*, June 2009.

10. X. Guo and X.-G. Xia, An elementary condition for non-norm elements, *IEEE Transactions on Information Theory*, Mar. 2009.

9. H. Wang, D. Wang, and X.-G. Xia, On optimal quasi-orthogonal space-time codes with minimum decoding complexity, *IEEE Transactions on Information Theory*, Mar. 2009.

8. H.-M. Wang, X.-G. Xia, and Q. Yin, Computationally efficient equalization for asynchronous cooperative communications with multiple frequency offsets, *IEEE Transactions on Wireless Communications*, Feb. 2009.

7. H. M. Wang, X.-G. Xia, and Q. Yin, Distributed space-frequency codes for cooperative communication systems with multiple carrier frequency offsets, *IEEE Transactions Wireless Communications*, Feb. 2009.

6. H. Liao, H. Wang, and X.-G. Xia, Some Designs and normalized diversity product upper bounds for lattice based diagonal and full rate space-time block codes, *IEEE Transactions on Information Theory*, Feb. 2009.

5. H. Liao and X.-G. Xia, Diversity product properties of Lu-Kumar's space-time codes, *IEEE Transactions on Information Theory*, Feb. 2009.
4. S. Fu and X.-G. Xia, Recursive space-time trellis codes using differential enco *IEEE Transactions on Information Theory*, Feb. 2009.
3. Y. Li, W. Zhang, and X.-G. Xia, Distributive high-rate space-frequency codes achieving full cooperative and multipath diversities for asynchronous cooperative communications, *IEEE Transactions on Vehicular Technology*, Jan. 2009.
2. Y. Shang and X.-G. Xia, Space-time block codes achieving full diversity with linear receivers, *IEEE Transactions on Information Theory*, Oct. 2008.
1. X. Li and X.-G. Xia, A fast robust Chinese remainder theorem based phase unwrapping algorithm, *IEEE Signal Processing Letters*, Oct. 2008.

Published Conference Proceeding Publications

18. H. M. Wang, X.-G. Xia, and Q. Y. Yin, Full Diversity Achieving Analog Network Coding for Asynchronous Two-Way Relay Networks with Linear Receivers, the Proc. ICC, Kyoto, Japan, June 5-9, 2011.
17. H. M. Wang, Q. Y. Yin, and X.-G. Xia, Fast Kalman Equalization for Coo perative Relay Networks with Both Time and Frequency Offsets, the Proc. ICC, Kyoto, Japan, June 5-9, 2011.
16. L. Shi, W. Zhang, and X.-G. Xia, A Design of High-Rate Full-Diversity STBC with Low-Complexity PIC Group Decoding, the Proc. Globecom, Miami, FL, Dec. 6-10, 2010.
15. Y. Shang, D. Wang, and X.-G. Xia, Flexible Signal Space Diversity Techniques From MDS Codes With Fast Decoding, the Proc. Globecom, Miami, FL, Dec. 6-10, 2010.
14. X. W. Li and X.-G. Xia, Multiple-frequency interferometric velocity SAR location and imaging of elevated moving target, the Proc. ICASSP 2010, Dallas, TX, March 14-19, 2010.
13. X. W. Li, X.-G. Xia, and H. Liang, A Robust Chinese Remainder Theorem with its Applications in Moving Target Doppler Estimation, Proc. IEEE International Radar Conf., Washington, May 10-14, 2010.

12. T. Xu and X.-G. Xia, On Space-Time Code Design with A Conditional PIC Group Decoding, the Proc. 2010 International Symposium on Information Theory, Austin, TX, June 2010.

11. W. Zhang, L. Shi, and X.-G. Xia, A Systematic Design of Space-Time Block Codes with Reduced-Complexity Partial Interference Cancellation Group Decoding, the Proc. 2010 International Symposium on Information Theory, Austin, TX, June 2010.

10. H. M. Wang, X.-G. Xia, and Q. Yin, A Simple Design of Space-Time Block Codes Achieving Full Diversity with Linear Receivers, the Proc. Globecom 2009, Honolulu, Hawaii, Nov. 30-Dec. 4, 2009.

9. W. Zhang and X.-G. Xia, A Systematic Design of Space-Time Block Codes Achieving Full-Diversity with Partial Interference Cancelation Group Decoding, the Proc. Globecom 2009, Honolulu, Hawaii, Nov. 30-Dec. 4, 2009.

8. Z.-F. Li and X.-G. Xia, Time Domain Interference Cancellation for Alamouti Coded Cooperative OFDM Systems with Insufficient CP, Prof. International Symp. On Information Theory (ISIT), Seoul, South Korea, June 28-July 3, 2009.

7. H. M. Wang, X.-G. Xia, Q. Yin, and L. Bai, A Distributed Linear Convolutive Space-Frequency Coding for Cooperative Communication Systems with Multiple Frequency Offsets, the Proc. of ICC 2009, Dresden, Germany, June 14-18, 2009.

6. F. Tian, X.-G. Xia, W.-K. Ma, and P.C. Ching, Full Diversity under Multiple Carrier Frequency Offsets of A Family of Space-Frequency Codes, the Proc. ICASSP 2009, Taipei, Taiwan, April 19-24, 2009.

5. F. Tian, X.-G. Xia, W.-K. Ma, and P.C. Ching, Full Diversity under Multiple Carrier Frequency Offsets of A Family of Space-Frequency Codes, the Proc. ICASSP 2009, Taipei, Taiwan, April 19-24, 2009.

4. Z. Li and X.-G. Xia, A Distributed Differentially Space-Time-Frequency Coded OFDM for Asynchronous Cooperative Systems with Low Probability of Interception, the IEEE Globecom 2008, New Orleans, Dec. 2008.

3. H.-M. Wang, X.-G. Xia, and Q. Yin, A Distributed Space-Frequency Coding for Cooperative Communication Systems with Multiple Carrier Frequency Offsets, the IEEE Globecom 2008, New Orleans, Dec. 2008.

2. H. M. Wang, X.-G. Xia, Q. Yin, and W. Wang, Computationally Efficient MMSE and MMSE-DFE Equalizations for Asynchronous Cooperative Communications

with Multiple Frequency Offsets, Proc. Internal. Symp. Information Theory (ISIT), Toronto, Canada, July 2008.

1. X. Guo and X.-G. Xia, On Full Diversity Linear Dispersion Codes with Partial Interference Cancellation Group Decoding, Proc. Internal. Symp. Information Theory (ISIT), Toronto, Canada, July 2008.

E. **Collaborators**:

Huiming Wang, Wenjie Wang, and Qinye Yin from Xi'an Jiao Tong University, China; Bin Li, Huawei Tech.; Moon Ho Lee, Chonbuk National University, South Korea; Feng Tian, K. Ma and P. C. Ching, Chinese University of Hong Kong; Long Shi and Wei Zhang, University of New South Wales, Australia.

F. **Post-doctors, Students Supported and Partially Supported by the Grant**

Supported Ph.D. Students: Xiaoyong Guo (graduated with Ph.D.), Zheng Li (graduated with Ph.D.), Tianyi Xu